RELIABILITY ASSESSMENT OF THE GEOS A SPACECRAFT

PRC R-760

29 December 1965

Prepared for

National Aeronautics and Space Administration

PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIFORNIA WASHINGTON, D.C.

RELIABILITY ASSESSMENT OF THE GEOS A SPACECRAFT

PRC R-760

29 December 1965

Prepared for

National Aeronautics and Space Administration
Under Contract NASW-1180

PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIF. WASHINGTON, D.C.

FOREWORD

This reliability assessment report presents the result of an inter-disciplinary team effort that commenced in February of 1965. Although assessment studies on the GEOS A spacecraft have been completed as of the date of this report (29 December 1965), studies of GEOS A in-orbit performance are planned for 1966. Assessment studies associated with the GEOS B spacecraft design are underway and are expected to continue into 1966.

Electronic subsystem analyses were carried out by W. C. Graham, D. B. Levinson, M. D. Reed, and H. G. Thompson. Mechanical subsystem analyses were carried out by J. A. Kolkin, R. J. Mulvihill, and L. H. Simonsen. Reliability models were prepared by C. E. Bloomquist, with assistance from L. Roseman and C. H. Wilmot. Performance analyses of the attitude control and stabilization subsystem were carried out by C. H. Wilmot. R. J. Mulvihill served as project manager for this study.

ABSTRACT

18647

This report provides a summary of the GEOS A subsystem reliability assessments as well as the overall system assessment. In addition a reliability improvement study on the GEOS A clock and memory subsystem is discussed.

Assuming that the Doppler and transponder experiments have a reliability of one, the effectiveness figure-of-merit for the GEOS A spacecraft lies between 0.41 and 0.63. The lower limit corresponds to a zero value for the alternate optical logic, and the upper limit corresponds to a value of the alternate optical logic equal to the value of the memory controlled logic.

It is recommended that certain studies associated with command and telemetry channel assignments, complete review of the parts program, and improvement of the clock and memory design be carried out. A modification to the design of the optical beacon is also recommended.

Author

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF EXHIBITS

I. INTRODUCTION

Reliability assessment studies commenced during February of 1965. In keeping with the imminence of the GEOS A design freeze, Planning Research Corporation (PRC) concentrated its efforts on identifying and advising on design improvements in the areas which were found or expected to be critical. Critical areas were grouped as indicated below and then ordered according to their criticality:

- Design areas (usually subsystems or parts thereof) where decisions relative to reliability had to be made prior to the GEOS A design freeze
- Design areas which were identified from reviews by NASA Headquarters, NASA Goddard, Applied Physics Laboratory, or PRC as potential areas for reliability improvement
- Design areas which, during the reliability modeling of subsystems, appeared as potential areas for reliability improvement

As a result, the following spacecraft subsystems were studied, with emphasis generally in accordance with their order:

- Clock/memory/alternate optical logic, with special emphasis on desirability of retaining the alternate optical logic
- Command subsystem
- Power supply subsystem
- Thermal control
- Gravity gradient stabilization
- Telemetry subsystem

During the course of the GEOS A study, a contract amendment was issued which provided that additional studies be made on the reliability of the optical beacon experiment and the Douglas yo-yo de-spin device, as well as conduct special studies on the clock and memory.

In addition to the above studies carried out under the general category of spacecraft reliability assessment studies, a study was undertaken on the operational reliability of the GEOS A spacecraft. The results of this study generally have been in the form of diagnostic routines for the analysis of in-flight spacecraft failures, as well as decision-action charts related to these same spacecraft failures.

This report is a summary report. Most of the details of the individual subsystem reliability assessments, as well as the operational reliability assessments, are found in technical advisement memoranda which shall be referred to throughout this report. This report also presents the results of analyses not previously reported in technical advisement memoranda. Typical of such results are those of the reliability improvement study on the clock and memory subsystem, as well as the parts program study for the clock and memory subsystem. In addition, an overall reliability model for the GEOS A spacecraft is reported for the first time in this report. This overall model combines results from the detailed subsystem reliability assessment studies reported previously in technical advisement memoranda.

II. SUBSYSTEM RELIABILITY ASSESSMENTS

A. GEOS A Command Subsystem

An effectiveness figure-of-merit (F.O.M.) reliability model was developed for this subsystem. The value assigned to each of the degraded states considered in the model was related approximately to the expected fraction of the total number of the 64 commands which were usable given a degraded state. The overall F.O.M. derived was equal to 0.771. A complete discussion of the analysis as well as the results are presented in Reference 1.

Two modifications to the design were set up and exercised in the model. These modifications, which were concerned with the failure effects that cause the loss of the entire command subsystem, were (1) making the ground line to the matrix SCR's switchable, and (2) AC-coupling the drivers in the logic units to the SCR's in the matrix. The corresponding F.O.M. model reliability numerics were found to be 0.807 and 0.777 respectively for these modifications.

It was concluded by PRC that in general the design and implementation of the GEOS A command subsystem was very good. Although the two modifications exercised in the model showed an increase in the reliability, with modification 1 showing the greater increase, it was felt that the increase was not large enough to warrant a firm recommendation for the acceptance of either. On the other hand, the increase shown by modification 1 is not so insignificant that it can be ignored. It was also concluded that the overall reliability could not be increased much beyond that illustrated from modification 1 by further efforts toward reducing the probability of occurrence of loss of the entire subsystem.

PRC feels very strongly that the assignment of locations of commands in any matrix should be optimized with respect to reliability. This particular area will be investigated in a future study.

B. Contribution of the Alternate Optical Logic to the Reliability of the GEOS A Optical Beacon Electronics

A full discussion of this analysis, together with the results of the analysis, is presented in Reference 2. The optical beacon electronics consists of the clock and memory subsystem of the GEOS A spacecraft. The primary purpose of this subsystem is to provide inputs to the sequence controller of the optical beacon. The alternate optical logic (AOL) is a backup system to the memory and provides for the issuance of signals to the sequence controller upon ground command.

A reliability model was prepared for this subsystem. The approach taken in the assessment was to assume that the whole subsystem was a 2-state device. In actuality, 24 degraded states were found as a result of the failure mode and effect analysis. A maximum and minimum reliability were calculated, which bound the true reliability based on the 2-state device assumption. The upper bound is derived by assuming that all parts which cause a partial loss of function cause no loss at all (i.e., that they do not exist). The lower bound is derived by assuming that all parts that cause a partial loss cause complete loss. The maximum and minimum values of the reliability are given below.

$$\overline{R(t)} = 0.130 + 0.798V$$

$$\underline{R(t)} = 0.081 + 0.838V$$

where V = the relative value of the optical beacon electronics when using the AOL, as compared with the value when the system functions normally with a completely functional memory

If the AOL is completely removed, the corresponding values for the maximum and minimum bounds on the true reliability are 0.131 and 0.085 respectively. It is clear that, by comparing the "with AOL" and "without AOL" system predictions, the value of the AOL, under the assumptions used, would have to be less than 1 percent to justify its removal. It was concluded that, from a reliability viewpoint, it was strongly advisable on the basis of the assessment to retain the alternate optical logic.

C. Power Supply Subsystem

References 3 and 9 present in detail the analyses and results of these analyses which were performed on the power supply subsystem. Reference 3 presents the detailed observations made on seven aspects of the design of this subsystem. Reference 9 presents the details of a reliability assessment, provides the probability of obtaining any of the required outputs of this subsystem, either individually or in combination with each other, and provides an overall effectiveness F.O.M. for this subsystem. The value system utilized in the F.O.M. calculations is based on assigning the following relative values to each of the active GEOS A experiments.

Experiment	Relative Value	Normalized Relative Value
Optical beacon	5	5/12
Doppler	4	4/12
SECOR transponder	2	2/12
Range and Range Rate transponder	1	1/12

The numerical value for the F.O.M. was found to be equal to 0.935, which means that at the end of one year the power supply is expected to perform 93.5 percent of the function demanded of it.

D. Assessment of Thermal Design of the GEOS A Spacecraft

This analysis covered the steady-state performance of the GEOS A passive thermal control subsystem. However, comments relative to the transient performance were also made. The analysis of the steady-state performance was carried out by constructing a thermal analog model of the spacecraft and computing therefrom the steady-state temperatures for the worst-case orbit condition. A complete discussion of this analysis, together with the results, is presented in Reference 4.

It was concluded that the best design from the standpoints of both transient and steady-state heat transfer involved the use of insulation of the external panels with respect to the internal box coupled with limited conduction. That is, some radial conduction through the 8 truss sections was necessary. In addition, it was concluded that external conduction among the external panels was necessary. Provided the above recommendations for conduction paths are properly implemented, and using accepted values for the thermal resistance of the insulation to be used on GEOS A, together with approximate thicknesses to be utilized, it was concluded that the passive GEOS A thermal control subsystem is capable of maintaining the spacecraft temperatures at suitable values. The reliability of the thermal control subsystem is therefore directly related to the reliability of maintaining the conduction paths mentioned above. These conduction paths are to be controlled by the conducting properties of fiber glass buttons, which insulate the external panels from the truss sections, and by panel conduction bands (clips), which provide paths among the external panels. Further investigations should be carried out to determine the reliability of these fiber glass buttons and panel conduction bands.

E. Analysis of Gravity Gradient Stabilization Subsystem Performance

Reference 5 provides the details of this analysis. The analysis was based on a gravity gradient stabilization system consisting of the NRL 60-foot boom and the General Electric eddy current damper, which is mounted at the end of the boom. The important conclusions drawn from this analysis are:

1. For all practical purposes, pitch vibrations are damped out within 1 day after capture.
2. For all practical purposes, yaw rotations are damped out in 1 or 2 orbital periods.
3. In the event of upside-down capture of the spacecraft, an inversion maneuver can be accomplished by retracting the boom to 30-foot extension and then extending the boom after several minutes.

F. Reliability Analysis of De-Spinning Capability of GEOS A With Special Emphasis on the Yo-Yo De-Spin Device

This analysis was undertaken to provide a basis for a decision as to whether or not it was desirable to incorporate magnetic hysteresis de-spin rods in the GEOS A spacecraft. It was recognized that a significant weight penalty must be paid if these rods are installed. Reference 7 presents a detailed analysis of this problem. An overall effectiveness F.O.M. model is developed in Reference 7, which represents the de-spinning actions involved, namely, (1) release of the yo-yo de-spin weights, (2) extension of the boom (this generally increases the moment of inertia about the spin axis), and (3) damping action of the General Electric (G.E.) eddy current damper. In addition, if the magnetic hysteresis rods are utilized, the spin rate is damped out exponentially. The reliability of the yo-yo de-spin device was found to be equal to 0.997. It is equal to the F.O.M. when no credit is taken for any of the other de-spinning actions.

Thus the conclusion was reached that there appears to be no strong requirement for the magnetic hysteresis de-spin rods. In the event that magnetic hysteresis rods are used, they do provide an adequate back-up in the unlikely event of failure of the yo-yo de-spin device. It was not possible to determine whether the extension of the boom and the damping action of the G.E. damper would provide an adequate back-up, since the results of the G.E. dynamics analysis were not complete at the time this study was performed. It is intended to include this consideration in a follow-on effort. However, since the reliability of the yo-yo de-spin device by itself is so high, the inclusion of the effect of the boom and damper will not change the overall de-spinning F.O.M. significantly. It will remain at approximately 0.997.

G. Optical Beacon Reliability Assessment

The reliability of the GEOS A optical beacon experiment depends on the reliabilities of (1) the optical beacon power supply, (2) the command subsystem, (3) the clock and memory subsystem, and (4) the optical beacon. Results of reliability assessments on the first three of these subsystems are reported upon above and are given in References 9, 1, and 2, respectively.

Reference 8 deals with the reliability assessment of the fourth item, that is, the optical beacon itself. In addition, this reference provides an overall model wherein the overall reliability, that is, the probability of obtaining the normal function of the optical beacon experiment at the end of 1 year, is computed. In Reference 8 the effectiveness F.O.M. model for the optical beacon was exercised for the present design configuration and for three design modifications. These modifications were (1) removal of one relay from each pair of power relays in each flash assembly, (2) addition of two more power relays to each flash assembly, with contacts in series redundancy with present relay contacts, and (3) increased redundancy in the sequence controller. The value system used in this effectiveness F.O.M. model was based on the relative value of the illumination to each of the principal types of cameras to be used given each of the model states. The numerical result for the present design of the optical beacon is as follows: F.O.M. (maximum): 0.911, F.O.M. (minimum): 0.843. The numerical results of exercising the model for the three design modifications are as follows:

- Modification 1, maximum: 0.922; minimum: 0.854
- Modification 2, maximum: 0.939; minimum: 0.870
- Modification 3, maximum: 0.948; minimum: 0.946

The 1-year F.O.M.'s for each of the four subsystems associated with the optical beacon experiment are as follows:

power	0.91
command	0.77
clock and memory	0.081 + 0.838V

where V = the relative value of the alternate optical logic as defined above

optical beacon	0.84

The clock and memory and optical beacon F.O.M.'s represent the minimum values for their predicted range. An estimate of the overall F.O.M. is obtained by the product of the above F.O.M.'s. The estimated 1-year F.O.M. for the optical beacon experiment is 0.048 + 0.47V. This F.O.M. can only be considered high if the relative value of the alternate optical logic V is considered to be high. The value of the F.O.M. is controlled primarily by the F.O.M. value of the clock and memory, which again is not high unless the relative value of the alternate optical logic is considered to be high.

From the standpoint of reliability, the present design of the EG&G optical beacon appears very good. Parallel redundancy is used in many parts of the design. Modification 3, which incorporates increased redundancy within the sequence controller, resulted in a significant increase in the minimum value of the optical beacon F.O.M. Considering the whole optical beacon experiment, it was found that the command subsystem, optical beacon power supply, and the optical beacon have a high probability of performing their functions for 1 year. The clock and memory subsystem, however, has a comparatively low 1-year reliability, unless the value of the alternate optical logic mode is considered to be almost equal to that of the memory mode. Of course, the reliability of the clock and memory subsystem without the alternate optical logic might be improved (raised). This possibility was investigated, as discussed in Section IV.

H. GEOS A Telemetry Subsystem Reliability Assessment

Reference 11 presents a detailed assessment of the telemetry subsystem reliability, together with the results of this analysis. An effectiveness F.O.M. model was constructed for this subsystem. The value system used was based on assigning equal value to each of the commutated data channels. The resultant F.O.M. was found to be equal to 0.54 (indicating roughly that the subsystem is expected to be 54 percent available at the end of 1 year). It should be pointed out that the primary value of the GEOS A spacecraft is associated with its experiments and that none of the experiments utilizes the telemetry system to transmit the experimental data. The telemetry subsystem accumulates value indirectly in the following way. The telemetry subsystem provides a means of indicating the status of the spacecraft. An exact knowledge of the status of the spacecraft is useful in providing for better utilization of the experiments. It is intended in the future to pursue the study of the indirect value of the individual telemetry points to the mission and to optimize the assignments of these telemetry points to the individual commutators, subcommutators, and telltale registers. With regard to the calculated F.O.M. indicated above, it must be concluded that it is highly probable that the telemetry subsystem will be in a degraded state at the end of 1 year. However, it is not likely that this degraded state of the telemetry subsystem will result in any appreciable loss in value accruing to the experiments.

III. OPERATIONAL RELIABILITY ASSESSMENT OF THE GEOS A SPACECRAFT

Reference 10 provides a detailed assessment of the operational reliability of the GEOS A spacecraft. This assessment consists of an analysis of in-orbit spacecraft failures together with recommended actions. Failure diagnostic routines and decision-action charts have been prepared which require two sources of spacecraft information: telemetry data and data from experiments. In the conduct of the analysis, it was not assumed that the telemetry indication is always correct.

An application of decision theory to decisions involving the redundant command converter was carried out to determine the effect of failure of a single telemetry channel on the decision-action procedures. It was demonstrated that if corroborating evidence based on data from other nonfailed telemetry channels is utilized, then no significant uncertainty remains with respect to decision making; thus the problem of obtaining incorrect telemetry data on a single channel and therefore taking a wrong action was found to be inconsequential if corroborating evidence from other telemetry channels is utilized. The diagnostic routines and decision-action charts presented in Reference 10 reflect the philosophy of seeking corroborative evidence.

The application of decision theory to GEOS operational reliability in the grosser situation where there is substantial loss of telemetry and concomitant increase in uncertainty is expected to result in situations where the best decision can yield results which are not made intuitively. This application is presently under consideration.

IV. RELIABILITY IMPROVEMENT STUDY - CLOCK AND MEMORY SUBSYSTEM

This study consisted of two primary tasks: (1) an analysis of the clock and memory subsystem with a view toward modifying the design in such a way as to improve its reliability, and (2) a review of the Applied Physics Laboratory parts program for the parts used in the clock and memory subsystem. The objectives of the latter task were to establish whether improvements could be made in the parts program, which could significantly improve the reliability of the clock and memory subsystem, and to determine through review of the parts program the most realistic part failure rates to be employed in reliability assessments of the clock and memory.

A. Reliability Improvement Study of the GEOS A Clock and Memory Subsystem Design

1. Circuit Analysis - Memory Core Circuits

A cursory analysis of the memory circuits associated with the memory cores was made. Exhibits 1, 2, and 3 present the reliability block diagrams for the clock and memory. The memory circuits, which are shown in block 7 of Exhibit 3, included the 5 by 13 coincidence switch, the 3 by 7 coincidence switch, the sense amplifier, the timing and reset circuit, and the inhibit stabilizer circuits. It was not necessary to carry out a special circuit analysis for the memory control unit since the implementation of the memory control logic is performed primarily by integrated circuits. The use of integrated circuits for this application has been found to be in accordance with good design practice.

The object of the analysis of the memory core circuits was to determine if the present memory could be made more reliable by either reducing the total number of parts or by making design modifications. No attempt was made in this initial effort to justify the operational function of the memory and its associated equipment.

As a result of this analysis, it was concluded that the 5 by 13 and 3 by 7 coincidence switches and the sense amplifier are designed with the minimal number of parts to meet the operational functions required of the

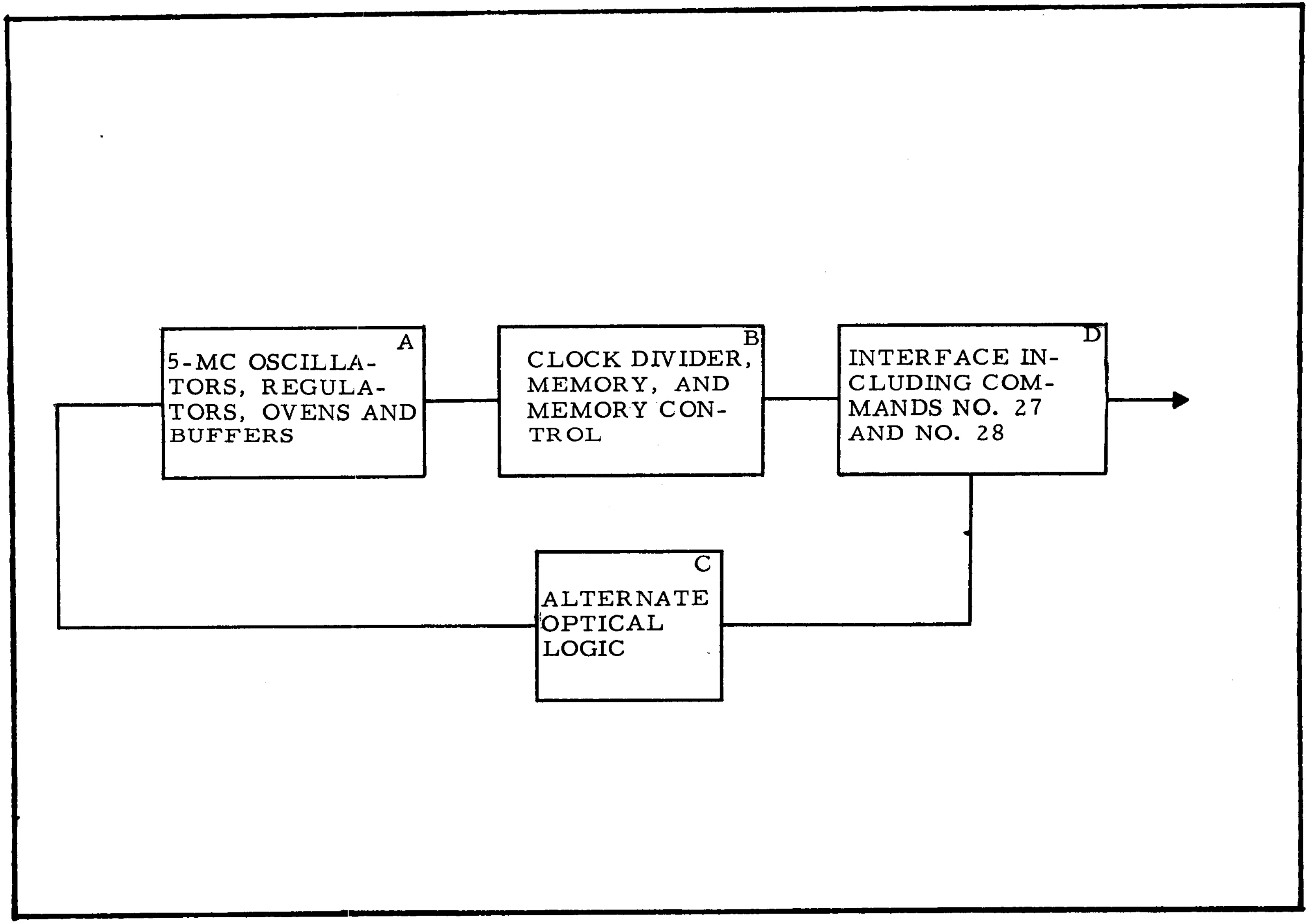

EXHIBIT 1 - CLOCK AND MEMORY RELIABILITY BLOCK DIAGRAM

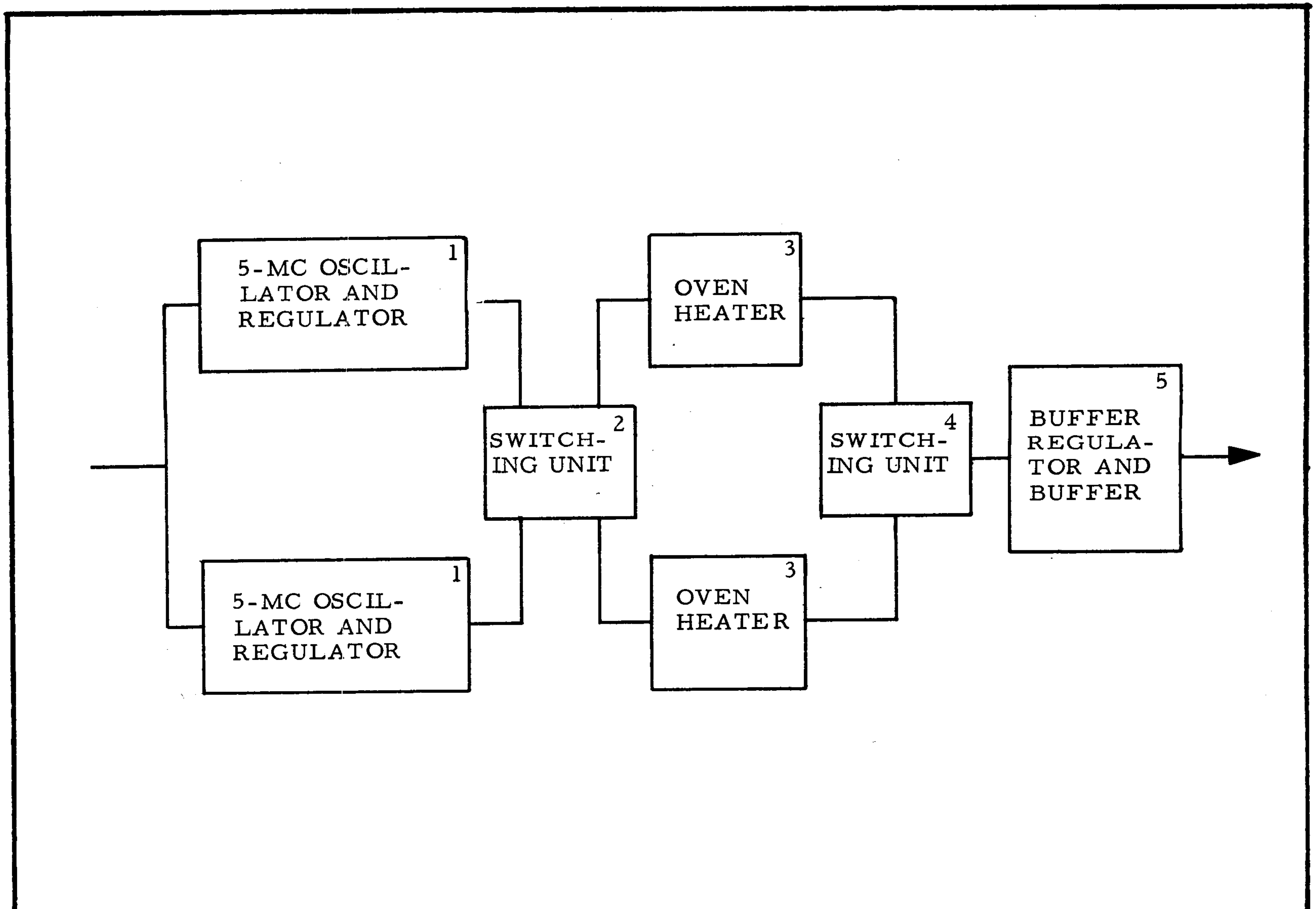

EXHIBIT 2 - BLOCK A RELIABILITY BLOCK DIAGRAM

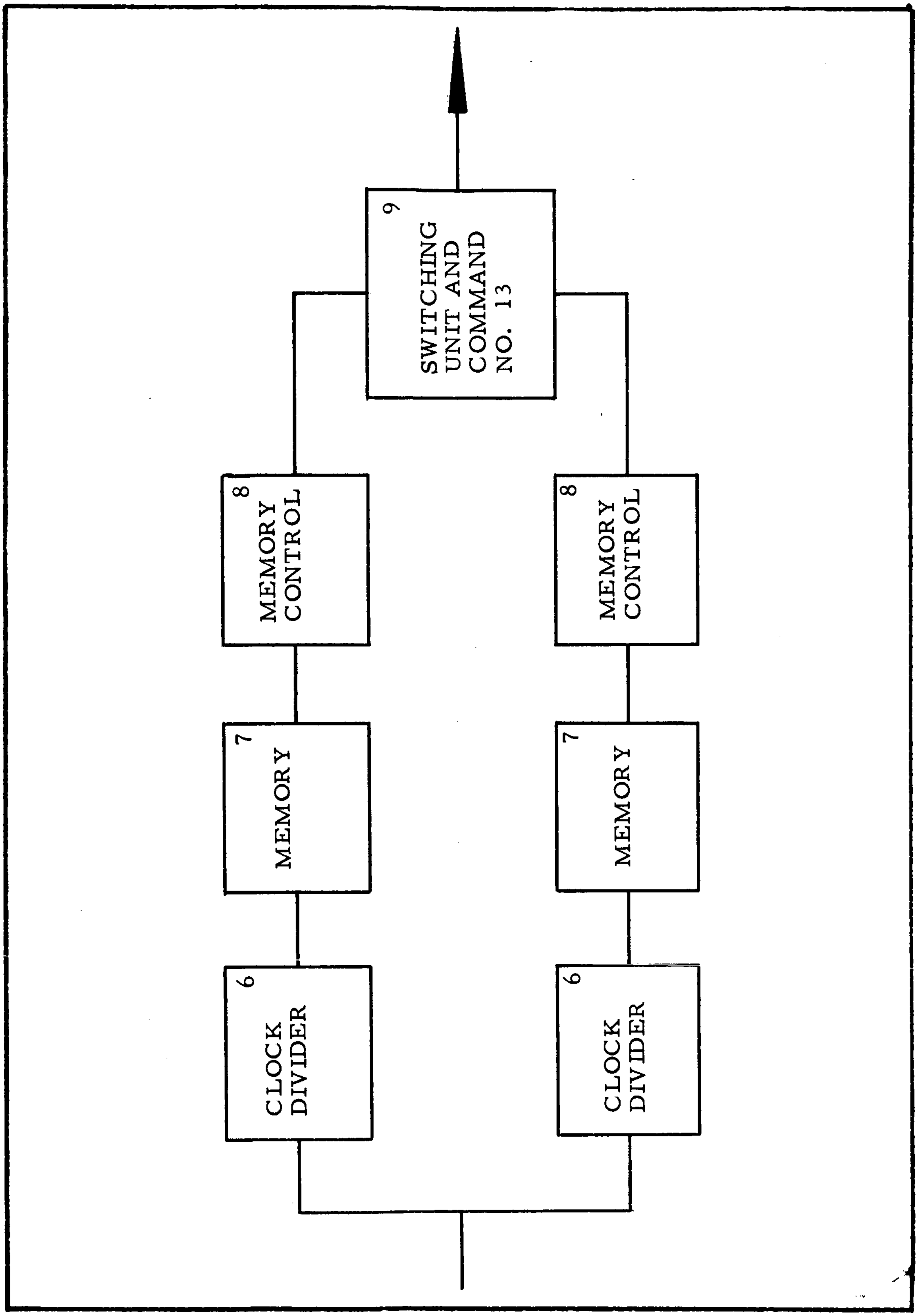

EXHIBIT 3 - BLOCK B RELIABILITY BLOCK DIAGRAM

circuits. Other circuits of the memory, such as the inhibit stabilizers, the delay circuits, and the reset drives, were not fully documented. It therefore was not possible to conclude with certainty that these circuits were designed optimally from the standpoint of parts minimization. From an overall point of view and from an operational standpoint, the memory unit and its associated electronics appear to be designed with the minimal number of parts for the present functional design. It was therefore concluded at this point that a fruitful area of investigation was the functional design itself.

2. Review of Functional Design of the GEOS A Clock and Memory

An investigation was then carried out to determine whether a better functional design for the GEOS A clock and memory subsystem could be found within the framework of the functional requirements placed on the memory. These functional requirements, which may be inferred from the capabilities of the present design as presented in Reference 13, are:

- As many as 59 flash sequences are required for each memory injection.
- A time period of as long as 68 hours may elapse between memory injections.
- An option of five or seven flashes per flash sequence is provided.
- Any combination of four flash tubes is selectable independently for each flash sequence.
- Continuous correction of memory clock frequency must be made in order to approach synchronism of flash sequences with Universal Time.
- The capability of generating a flash sequence during any UT minute between memory injections is required.

The number of possible sequences of 59 flash times in 1440 minutes of nighttime operation is

$$N = \frac{1440!}{59!\ 1381!} \approx 2^{351}$$

With ideal nonredundant coding, which is practically unattainable, about 351 flash time bits would have to be stored in the memory to specify 59 flash times for each injection.

In the present memory functional design, there are 59 flash time words - one word per flash sequence. The first 12 bits in each word specify the number of minutes remaining until the first flash of a sequence occurs. Thus, the present memory stores 708 bits of flash time data.

The above result leads to the possibility of encoding the flash time and other data so as to reduce the total number of bits in the memory, with possible consequent reduction in the total number of memory subsystem parts. Such a reduction might increase reliability.

a. Format Changes

The following format changes, which do not substantially alter the functional capability of the memory, were considered:

(1) Flash Time Data

A simple way to approach the ideal minimum number of flash time bits would be to let each flash time portion of a flash time word represent the number of minutes from the preceding flash time. For random flash times, this interval would be greater than 128 minutes in only about 0.6 percent of the cases. The number of flash time bits in each flash time word could be limited to seven. The total number of flash time bits would be 7 x 59 = 413.

(2) Light Selection Data

The present system uses four bits in each flash time word to specify the lamp bank complement. This could be reduced to two bits per word to specify any one of four intensity levels, while four bits at the end of the format could specify the particular lamps to be used in each injection period.

(3) Normalizer Data

The normalizer data presently occupies four bits per flash time word plus 20 bits in word 60 for a total of 256 bits. These bits represent the equivalent of an 8-bit decimal number, which is the pulse frequency to be subtracted from the clock frequency to provide correction. The number could either be encoded in standard binary form with about 27 bits placed at the end of the format, or stored in a separate register. The bits could be gated with the bits of a binary counter to yield the correction pulse train.

An additional bit in each flash time word is used to specify a 5 or 7 flash sequence. Thus the total bit requirement is 413 + 124 + 27 + 59 = 623. The next convenient size for relatively prime diagonal scanning is 2 x 5 x 7 x 9 = 630 bits, which is a substantial reduction from the present 1,365 bits. Thus, the 2 by 5 and 7 by 9 coincidence switch matrices replace the present 3 by 7 and 5 by 13 matrices.

The object of the above format changes is to decrease the number of parts in the memory subsystem. The memory plane would be reduced from 1,365 to 630 cores. The number of parts in the memory driver circuits would be reduced from 270 to 229 parts. However, the rate of catastrophic failure for these circuits is principally determined by the number of transistors and diodes. Transistors would be reduced from 35 to 32, and diodes from 28 to 23.

These parts reductions are the result of the elimination of redundant data from the present format. An error in any of the modified flash time bits would cause all the succeeding flash times in the injection to be in error. To reduce the probability of a serious error to 0.1 would require a bit error rate on the order of 10^{-3} per bit. The format changes place a more stringent requirement on the bit error rate.

b. Required Modifications of the Timing Control Logic

The above format changes for the memory proper require considerable modification of the timing control logic of the memory and control unit. This modification involves the following changes:

(1) The change in memory size from 1,365 bits to 630 bits requires a memory clock rate of 10.5 cps rather than 22.75 cps. In order to generate this rate, a modification to the timing circuit configuration is required. This problem has been investigated, and no convenient configuration has been devised which would result in the generation of the 10.5 cps memory clock signal and the 186.875 cps signal to the

Doppler system, while using the 4.99975 mc clock input and maintaining the accuracy of the present system. It is assumed that such a configuration can be devised which does not increase the timing parts count by a significant amount; however, in light of the conclusions based on the format changes, it was decided that the amount of effort required to devise such a configuration was not warranted.

(2) Under the discussed memory format, each word used for timing counts the minutes since the previous flash sequence rather than the time from the start until a given flash sequence. The memory control circuitry must therefore be modified. A possible modification involves the addition of four integrated circuit modules.

(3) The use of two bits per word, rather than four, for flash tube select indication requires that certain flash tube select data be encoded in several words at the end of the memory and that the control circuitry be changed. These changes require the addition of 14 integrated circuit modules.

(4) By removing the normalization function from the memory, the format change requires that this function be handled by special equipment. This equipment consists of approximately 72 integrated circuit modules.

(5) As a result of the format changes, several logical functions are no longer necessary. This results in the elimination of 12 integrated circuits.

c. Net Effect of Format Changes

The three format changes discussed above result in a reduction of 1,365 to 630 cores in the memory plane, as well as a reduction of 41 parts in the memory drivers. However, a net increase of 78 integrated circuits would be required for the timing control logic. This is about a 40 percent increase over the number of integrated circuits presently used in the memory and control unit. About 80 percent of the added integrated circuits are required to perform the normalization function which represented 20 percent of the size of the original memory.

In conclusion, in view of the more stringent requirements on the bit error rate and the increase in the required number of integrated circuits and the small reduction in memory driver circuit critical parts, the three format changes discusses above do not, from a reliability point of view, appear to be an improvement over the present design for the present set of functional requirements. As part of a continuing effort in the area of clock and memory reliability improvement, a further study will be made to determine the degree to which the functional requirements can be relaxed within the framework of the GEOS A and B mission requirements. The effects of this relaxation on clock and memory design and reliability for the GEOS B spacecraft will be evaluated. In addition, studies will be initiated to evaluate the improvement in reliability provided by allowing for switchable redundancy of the individual units (6, 7, 8) in Exhibit 3.

B. Review of the Applied Physics Laboratory Parts Program as Applied to the Clock and Memory Subsystem

This section presents the results of a review of the electronic parts program used by the Applied Physics Laboratory (APL) for the GEOS A clock and memory subsystem. Assemblies covered in the review were the clock divider, memory, and memory control.

The principal investigating organization for this study was Reliability Research and Technology, Inc. (RRT), a subsidiary of Planning Research Corporation. Following completion of the RRT effort, PRC conducted a sample review of the APL control drawings (parts procurement specifications) at APL to verify the principal comments made by RRT.

1. RRT Investigation

Information was derived from evaluation of APL parts lists, PRC/APL parts program discussion notes, and direct interviews with cognizant personnel at APL. The APL control drawings, which present the detailed procurement specifications for the GEOS A parts, were not made available to PRC or RRT by APL at the time that this investigation was being carried out. The findings of this investigation by RRT are discussed in the following subsections.

a. Parts Selection and Application

Designers received parts selection guidance from the APL electronic parts index (sections 3000, 5000, 5200, and 5300). These lists contain a tabulation of electronic parts which are covered by APL specifications. As discussed in a subsequent section, some of the items on the list are not state-of-the-art high reliability parts. APL indicated a reluctance to use the Established Reliability and MIL-38100 high reliability space parts because they did not have experience with the specific items and sources. They further stated that many of the specifications were not available in the early design phases. Part application and stress criteria were left up to the designer. No independent stress, worst case, or drift/tolerance analyses were performed. No uniform derating criteria were established for design.

b. Part Procurement Specification and Procurement Practices

The available parts lists indicate that 20 of 31 part types are covered by APL procurement specifications. It is assumed that the other 11 part types are covered by vendors' specifications. APL procurement specifications are in the form of control drawings and, in general, provide requirements supplemental to a vendor or military specification. Some of the parameters are therefore not controlled by APL, except through a change notice provision in the APL specification. Since APL had not made the control drawings available for review at the time of this evaluation, the adequacy and technical accuracy could not be verified.

The procurement philosophy of APL leans heavily upon 100 percent screening and conditioning such as burn-in and thermal cycling. The vendors are permitted to establish the screening test requirements and rejection limits subject to APL review and approval. The tests are performed by the parts manufacturer. No consistent approach is applied to the monitoring of screening tests or the evaluation of test data. Most data is received, but is reviewed only after problems develop. No numerical analysis is performed to establish patterns or trends and identify departures from the norm.

c. Usage Profile

Exhibit 4 presents a usage tabulation derived from the parts lists. A reasonable standardization effort is indicated. It is interesting to note that all parts in the clock divider are used in the memory and memory control. The active element usage of six transistor types and three integrated circuit types may be marginal for 1,141-part assembly (i.e., the active element usage possibly should be less); however, further circuit analysis will be necessary to substantiate this statement. Such an analysis will be carried out for the GEOS B design.

A rating column is integral to the tabulation, but was not completed since the procurement specifications were not available for review. The rating index of 1 to 5 is typically used in such tabulations and its definition is shown in the lower left hand corner.

A brief evaluation was made of resistor and capacitor selection. Examples of the results of this review are given below. The information regarding APL control drawings is the result of a sample review conducted by PRC with the authorization of APL.

Item	Comment
Resistor MMF-T-2	Has been redesignated MMC and is controlled under International Resistor Corporation's "PAR" program.
Resistor DM-10	MIL-R-10509 Deposited Carbon. The vendor recommends replacement with a type CEA controlled reliability part. APL has been buying type CMR-HRDM where their schedule permits.
Resistor MEA and MEB	The vendor recommends replacement with controlled reliability part type CAA, level 2, and type CCB, level 2, respectively. APL requires that these resistors conform to all the applicable requirements of International Resistor Corporation Established Reliability Specification 345, "PAR" program, reliability level 4. APL control drawing CD-3016 covers these parts.
Resistor DEB	Cannot identify.
Trimmer Spectrol 50	70°C part, considered marginal for flight application. This part type is covered by APL control drawing CD-3021. As per this specification, the power rating is 1.0 watt to 50°C per MIL-R-27208. Above 50°C the requirement is for linear derating to zero power at 150°C.

23 ①

EXHIBIT 4 - PARTS USAGE TABULATION

Memory and Memory Contro

Nomenclature	Manufacturer	APL/ JHU CD	Manufacturers Part Numbers	RAT ING	71 22	71 32	71 42	71 62	72 22	72 42	72 62	72 82	74 52	76 12	78 22	7 4
Core	Electronic Memories Inc.		EMI-101-101		21	65										
Core	Electronic Memories Inc.		EMI-141-101		13	23										
Capacitor, Fixed Ceramic	Aerovox Corp.	3003	CR 89-90						3				2			
Capacitor, Fixed Ceramic	Aerovox Corp.	3004	MC80					7	7		3	3	4	1	2	
Capacitor, Fixed Ceramic	Aerovox Corp.	3005	NPO						1		3	1		6	1	
Capacitor, Fixed Tantalum	Sprague Electric Co.	3000	350D						2		1	1	4	3	3	
Capacitor, Fixed Tantalum	Sprague Electric Co.	3043	137D							1						
Diode, Zener	Hoffman	5006	IN746-IN759, IN957A-IN992A				3	3					5			
Diode	Micro Semi-Conductor Corp.		MMC 1101		10	18										
Diode	Raytheon	5001	IN3730(RD 750)				14	14					8			
Diode	Fairchild	5002	IN3064						1					12	2	
Diode	Hoffman	5005	IN702A-IN759, IN761-IN769A							3		1				
Filter, By Pass, '400-4245CPS		5311											2			
Inductor, Fixed RF	Nytronics, Inc. Essex Div.	3006	DECI-DUCTOR		7	13										
Inductor, Fixed RF	Nytronics, Inc. Essex Div.	3013	WEE				3	3	2		1	1		3	3	
Solid Circuit (Integrated)	Fairchild		9193051									9				
Solid Circuit (Integrated)	Fairchild		9193251									2				
Solid Circuit (Integrated)	Fairchild	5310									10			24		10
Sensitor	Texas Instrument		TI-TM-V8-56r				3	3								
Transistor	Fairchild		2N3117										1			
Transistor	Fairchild		2N2369A						6							
Transistor Si, NPN	Fairchild	5214	S-4855 (Spec. 2N2297)		13	23				3						
Transistor Si, NPN	Fairchild	5232	2N2920-2						2			2				
Transistor Si, PNP	Motorola	5222	2N2905A, 2N2907A				9	9		5		1	3	6	1	
Transistor Si, NPN	Texas Instrument	5223	2N2219, 2N2222				9	9		5		2	2	6	1	
Transformer	Sprague		43Z234				3	3								
Resistor	Int'l Resistance Cont.		MMF-T-2		13	23										
Resistor	Int'l Resistance Cont.		DM-10		10	18										
Resistor Fixed Metal Film	Int'l Resistance Cont.	3016	MEA, MEB, DEB										28	31	5	
Resistor Fixed Metal Film	Int'l Resistance Cont.	3038	CCM				46	46	24	28		8				
Resistor, Variable	Spectrol Electronics Corp.	3021	50--				3	3								
			Total		87	183	93	100	48	45	18	31	59	92	18	10

Rating Index

1 High Reliability
2 Controlled Production test
3 Military Specification
4 Commercial Limited Control
5 Commercial No-Control

7211
APL Drawing Numbers

Clock Divider

8 2	78 52	78 62	78 82	78 92	79 02	73 22	73 23	73 35	73 52	73 53	73 55	74 12	74 15	75 52	Total
															86
															36
		1													6
														3	30
		1			2									35	50
		2			3			2	2			1	1	3	28
															1
															11
															28
															36
					5									50	70
															4
															2
															20
		2			3			2	2			1	1	3	30
															9
															2
	9		10	10		13	10			11	7	10	13		137
															6
															1
														23	29
															39
															4
					4										38
					5										39
															6
															36
															28
		3			26			3	1				2	72	171
															152
															6
	9	9	10	10	48	13	10	7	5	11	7	12	17	189	1,141

Capacitor 350D	High reliability solid tantalum.
Capacitor 137D	Can be replaced with a high reliability version type 337D. This part type is covered by APL control drawing CD-3043. APL has stated that they had originally intended to buy 337D, but this type capacitor was not commercially available in time.
Capacitor CR 89-90	Commercial part not recommended for flight usage. The vendor recommends controlled reliability part. This part type is covered by APL control drawing CD-3003, which specifies a high reliability part.
Capacitor MC 80	Commercial part has low temperature solder. HMC 80 is recommended. Jet Propulsion Laboratory has a high reliability specification on this part. This part type is covered by APL control drawing CD-3003, which specifies a high reliability part.

2. PRC Investigation

In view of the results of the investigation performed by Reliability Research and Technology as given above, PRC attempted to verify whether the comments presented above were applicable or whether the lack of availability of the control drawings for review had resulted in some incorrect parts evaluations. APL agreed to a sample review of the control drawings on their premises. APL feels that all their control drawings specify high reliability parts. As part of the sample review, PRC studied CD-3004, Capacitor, Fixed HI-K Ceramic Round, Molded (MC 80). Section IV of this specification states, "These units shall be manufactured on an established high-reliability line which has all the necessary in-process controls to insure an output of high reliability capacitors." Sampling tests covering the voltage-temperature characteristic, moisture resistance, and 1,000-hour life test at twice rated voltage and 125°C are also required. APL considers CD-3004 to specify the high reliability version of MC 80. References 12 and 13 indicate that corrections have been made by the manufacturer which eliminate problems (related to two failures in S-52 spacecraft) encountered with this capacitor. Reference 12, an APL memorandum, specifies that for space applications, purchases of this component should be restricted to the high reliability version specified in CD-3004. A review of CD-3003, which covers the CR 89-90, indicates that APL has called for a high reliability version and has used wording similar to CD-3004.

Thus the limited sampling review of the control drawings carried out by PRC personnel at APL indicates that the control drawings reviewed call for high reliability parts. It should be recalled that the parts lists for the clock and memory subsystem indicate that 20 of 31 part types are covered by APL control drawings. PRC has confirmed that the balance of the part types are covered by vendors' specifications. Parts are purchased to commercial specifications only when the high reliability counterpart is not commercially available in time. APL then relies on intensive in-house screening to increase the effective part reliability.

3. Recommendations

It is recommended that the parts program review be continued and include the following items to be accomplished by APL with PRC review or assistance.

a. Application Review

A thorough assessment of application stress (electrical and environmental) and performance of worst case analysis on critical or marginal circuits. Application review should also consider the possibility of further reduction in part types.

b. Selection Review

Analysis of existing parts to determine possible direct substitution of parts with superior controlled reliability characteristics.

c. Screening Test Monitoring and Data Analysis

Sample monitoring of source screening test performance and test data.

C. Overall Conclusions of the Clock and Memory Reliability Improvement Study

A review of the clock and memory subsystem based on the present functional requirements has indicated that the present design is generally a good design from a reliability viewpoint. Significant reliability improvement could possibly be gained by providing for switchable redundancy among the clock divider, memory, and memory control units. Other format changes, which correspond to reduced functional requirements, could possibly result in an improvement in reliability. Further study for GEOS B in these two reliability improvement areas is planned.

A review of the APL parts program for the clock and memory reveals that there are many areas wherein the parts program could be systematically improved.

V. GEOS A SYSTEM RELIABILITY ASSESSMENT

A. Introduction

The objective of this section is to integrate the individual assessments into an overall assessment of the basic spacecraft and experiments. Because the time available for the development of a system model during the GEOS A study was limited, this analysis will, of necessity, be somewhat qualitative. If the limitations on the model are kept firmly in mind, however, the results should be indicative of the overall reliability of GEOS A.

The model to be used for the system may perhaps best be introduced by reference to Exhibit 5 and by a brief summary of the pertinent previous analyses.

An analysis has been made, in varying detail, of all the areas represented by the blocks in Exhibit 5 except for the Doppler, Range and Range Rate transponder, and SECOR transponder experiments.

The first block represents those items not requiring extended active operation, such as the attitude control subsystem, thermal control, basic structures, laser beam reflectors, etc. It is the conclusion of the PRC assessment team that this block contributes no significant propensity to system failure or degradation of total experiment information, given a successful launch.

The command subsystem analysis (Reference 1) showed that a very large number of subsystem states (256) were possible. Furthermore, each of these states could result in a number of different effects on the satellite in terms of loss of function of the experiments. For example, one of the 256 states may be described as "loss of one row (or column) from the command matrix." This single state may have 16 different effects on the function of the experiments, depending on which row (or column) is lost. However, with a minimum amount of manipulation of the command subsystem assessment, it can be determined that the probability of loss of no experiment functions whatever, due to failures in

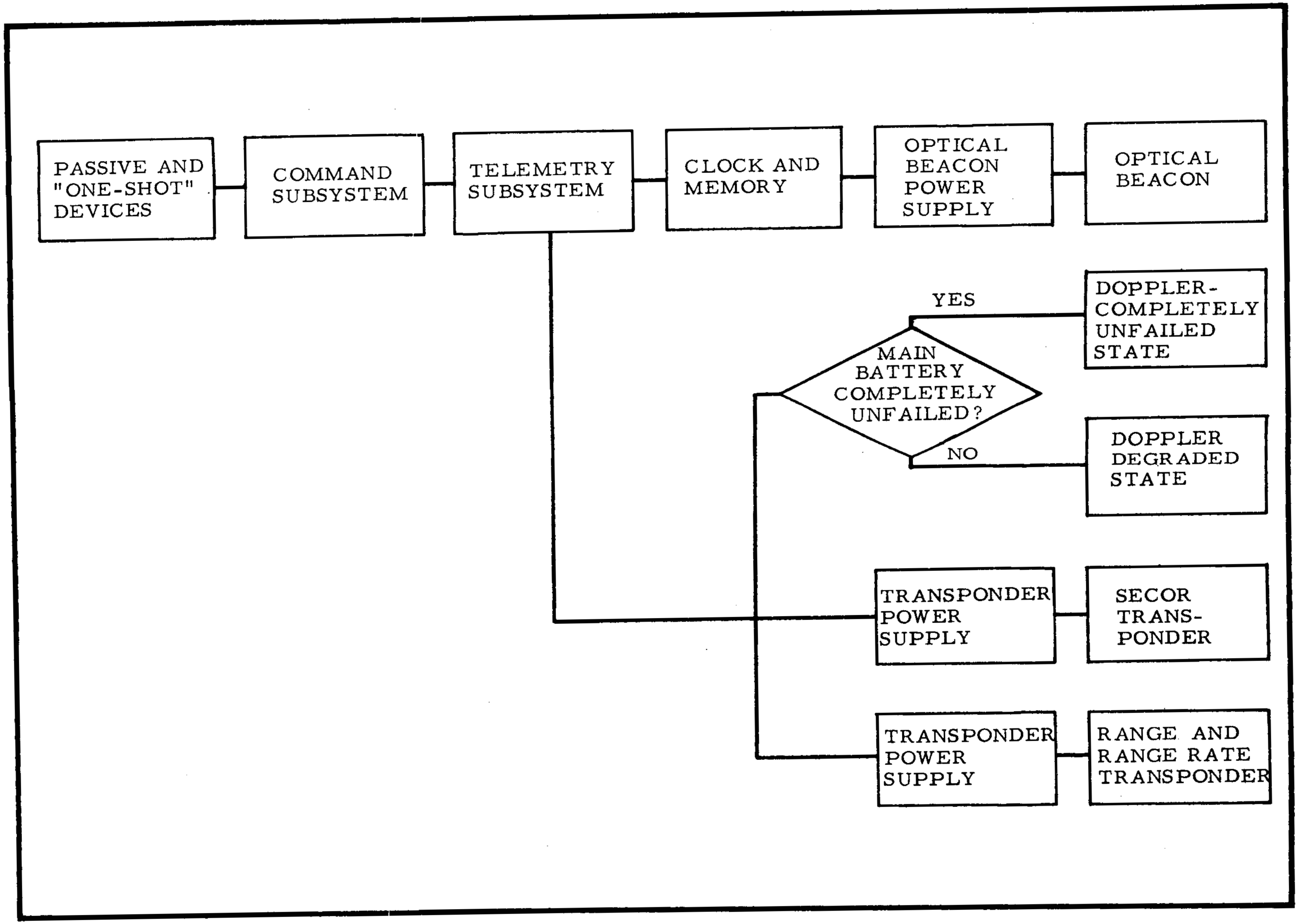

EXHIBIT 5 - GEOS A SYSTEM RELIABILITY MODEL

the command subsystem, is approximately 0.70. Since this is only about 10 percent lower than the F.O.M. for the subsystem, it will be conservatively assumed that the degraded states for this subsystem have zero probability. As a consequence of this assumption, it may be stated that the command subsystem causes no degradation with probability 0.70 and that it is completely lost to the satellite with probability 0.30, both probabilities being appropriate for 1 year's operation.

That portion of the telemetry subsystem having a direct bearing on experiment information output is quite small. Therefore degraded states, although highly likely in this subsystem (F. O. M. = 0.54, Reference 11), should have little direct effect on the value of the experiments. This indirect effect is treated in the operational reliability assessment (Reference 10). For the purpose of this assessment, only the direct effect will be considered and the reliability will be set equal to one.

The reliability F.O.M. for the clock and memory is reported in Section II. G of this report. The minimum value is 0.081 + 0.838V, where V is the relative value of the AOL.

The probability of each of the power supply outputs is given in Reference 9. The reliabilities, pertinent to this assessment, are given below.

Unit	Unit Reliability
Optical Beacon Power Supply	0.907
Main Battery	0.932
Transponder Power Supply	0.907

B. System Model

Before proceeding to a consideration of the experiments proper, an explicit formulation of the system model will be undertaken. The usual PRC approach is to consider all possible system states S_i (defined by various combinations of operable and inoperable components), determine the state probabilities $P(S_i)$, assign a value to each state

$V(S_i)$, and finally to derive a system F.O.M., as

$$\text{F.O.M.} = \sum_{i}^{2^n} P(S_i)\, V(S_i) \tag{1}$$

where n = the total number of system components

Under certain conditions this approach may be simplified considerably. In the present case, for example, it has been assumed that the value of GEOS A is accrued solely from the four experiments (shown in Exhibit 5) in an additive manner with relative weights as follows: Optical Beacon 5, Doppler 4, Range and Range Rate transponder 1, SECOR transponder 2. Under the further assumption of independence of failures between components, it may be demonstrated that

$$\text{F.O.M.} = \sum_{j} R_j V_j \tag{2}$$

where R_j = the probability that the j^{th} experiment is operable (or in a particular degraded state)

V_j = the normalized relative value of the j^{th} experiment (or a particular degraded state thereof)

and the summation is over all experiments (or all experiment states)

With the above assumptions, equation (2) is true at least as long as each satellite component is a 2-state device, i.e., either operates or fails. This condition can nearly always be satisfied by suitable definitions of components and is clearly satisfied in the present case, assuming the experiments themselves are 2-state devices.

For satisfactory operation of the optical beacon and the transponders, the corresponding power supply batteries must be in the unfailed state. The Doppler can operate on the main solar cells with the main battery in the completely failed state provided the spacecraft is not in eclipse. Therefore all of the experiments are either potentially operable or inoperable (depending on the state of the experiment package), except for Doppler, which is either completely operable or degraded depending solely on the operability or nonoperability of the main power supply battery (see Reference 9). That is, if the satellite is not in eclipse the Doppler is always assumed to be operable. When the satellite is eclipsed, the Doppler is operable only if the main battery is operable. The proportion of the GEOS A mission that will be eclipsed is approximately 20 percent. Thus equation (2) may be written more explicitly as

$$\text{F.O.M.} = \sum_{j=1}^{5} R_j V_j \tag{3}$$

where the various terms are defined in Exhibit 6.

Utilizing the subsystem reliability numerics derived thus far and Exhibit 6,

$$\text{F.O.M.} = 0.265(0.081 + 0.838V) + 0.229r_6 + 0.053r_7 + 0.106r_8 \tag{4}$$

where V is the relative value of the alternate optical logic
r_i is the 1-year reliability of the numbered units of Exhibit 6

An estimate of the relative 1-year utility (effectiveness F.O.M.) of the basic spacecraft design may be inferred by letting the experiment package reliabilities (r_i in equation (4)) approach unity.

For $V = 0$; F.O.M. = 0.41
For $V = 1$; F.O.M. = 0.63

Unfortunately, without numerical values for V, r_6, r_7, and r_8, or at least a means of deriving them, a single numerical F.O.M. for the total GEOS satellite cannot be determined. If all four unknowns are uniformly assumed to be, first zero; then, one-half; and finally, unity, F.O.M. goes from 0.02 to 0.33 to 0.63.

EXHIBIT 6 - DEFINITION OF TERMS FOR GEOS A FIGURE-OF-MERIT MODEL EQUATION

Experiment State j	Definition	Probability R_j	Value V_j
1	Optical Beacon Operable	$r_2 r_4 r_5$	5/12
2	Doppler Operable	$r_1 r_4 r_6$	4/12
3	Doppler Degraded	$r_4 r_6 (1 - r_1)$	3.2/12
4	Range and Range Rate Operable	$r_3 r_4 r_7$	1/12
5	SECOR Operable	$r_3 r_4 r_8$	2/12

The r_i refer to the reliability of the spacecraft units under consideration as follows:

i	Units	1-Year Reliability, r_i
1	Main Battery	0.932
2	Optical Beacon Power Supply	0.907
3	Transponder Power Supply	0.907
4	Command Subsystem	0.700
5	Optical Beacon Experiment Package and Clock and Memory	0.081 + 0.838V
6	Doppler Experiment Package	r_6
7	Range and Range Rate Experiment Package	r_7
8	SECOR Experiment Package	r_8

The basic conclusion to be drawn from this analysis of the overall GEOS A spacecraft reliability is that, in order for the spacecraft to perform its mission with a reasonable probability of success, it will be necessary that a major portion of the mission objectives with respect to the optical beacon experiment be accomplished by the use of the alternate optical logic and that each of the Doppler, SECOR, and Range and Range Rate experiments have a high reliability, that is, close to 1 for a 1-year period. Should the relative value of the alternate optical logic be negligible so as to approach zero, and the Doppler, SECOR, and Range and Range Rate experiments have a high 1-year reliability, then the F.O.M. is approximately 0.41, which may be interpreted as meaning that, at the end of 1 year, 41 percent of the mission value will be accumulated. Of course, should the above three experiments have a very low reliability in addition to the relative value of the alternate optical logic being negligible, the overall mission F.O.M. has been shown above to approach zero.

It should be reiterated that the above F.O.M. computations reflect the use of the failure rates which are presented in Reference 6, and which are based primarily on MIL Handbook 217. It has been demonstrated in the Telstar program that a carefully designed and implemented parts program can result in failure rate reduction of the order of a factor of 100. The review of the parts program for the memory, carried out by Reliability Research and Technology, Inc., has shown that reductions in the MIL Handbook 217 failure rate cannot be justified without completing a detailed review of the APL procurement specifications (control drawings).

The following means are available for improving the overall GEOS system F.O.M. They are:

1. Improve the reliability of individual subsystems and experiments. Possible candidates for improvement are (a) the clock and memory subsystem, (b) the command subsystem, and (c) the optical beacon experiment package.

2. Improve the parts program for the entire satellite so as to justify the use of failure rates lower than those specified in Reference 6.

3. Improve the operational aspects of GEOS by a more nearly optimum allocation of telemetry points to telemetry channels and commands to the command matrix (and thus raise the reliability of the command subsystem) and by continuing to delineate the appropriate command responses to indications of satellite malfunctions. A continuation of the studies presented in Reference 10 is planned as part of a follow-on effort.

4. It may be practical in future work to accurately reflect experiment value as a function of time. A significant portion of the optical beacon experiment value is accumulated at the time the short arc measurements are taken, thus forming a basis for intercalibration of the various geopositioning techniques. Since the short arc measurements probably will take place well before the end of the first year of operation, the expression of experiment value as a time function will probably have the effect of raising the 1-year GEOS F.O.M.

VI. COMMENTS ON GEOS A RELIABILITY ASSESSMENTS

It must be pointed out that the reliability assessments carried out on GEOS A are based on the design as reflected in the schematic drawings furnished to PRC by APL primarily during March, April, and May of 1965. The assessments, then, do not reflect the subsequent revisions. They do generally reflect the APL parts program; the review of the parts program, however, was limited to the clock and memory subsystem. The entire spacecraft parts program is scheduled for review.

The assessment does not reflect any of the results from the qualification and acceptance testing programs carried out at APL. In general, the data was not available in time. It is recommended that a task to incorporate qualification, acceptance, and other test results into the reliability predictions be approved as a follow-on effort. In such a task, the reliability estimates derived from tests would be factored into the predictions obtained from reliability models by using Bayesian statistical techniques.

Finally, the reliability assessments assume that quality control is perfect and that, if any fabrication errors arise, they are detected by quality control inspectors and instrumentation.

VII. RECOMMENDATIONS

It is recommended that the following studies be carried out as part of a continuing reliability assessment effort on the GEOS spacecraft.

1. Assignment of the command functions to the command matrix intersections in such a way as to optimize the effectiveness F.O.M. The objective here is to achieve a higher effective reliability for the command system.

2. Provision for an optimum assignment of telemetry points to telemetry channels. The study will be based on the general case of degraded telemetry and will provide for maximum utility of the spacecraft within the framework of the mission objectives. The application of decision theory is contemplated.

3. Complete review of the APL parts program.

4. Continued study of means of improving the design of the clock and memory from a reliability viewpoint. The provision for switchable redundancy among the clock divider, memory, and memory control units, as well as the effect of reduced functional requirements on reliability, should be evaluated.

It is recommended that a certain design modification to the optical beacon designated as Modification 3 be given serious consideration for implementation. This modification provides for (a) the increased use of internal redundancy within the sequence controller, and (b) an additional power relay in series with each of the power relays in each flash assembly. Details of this modification are presented on page 6 of Reference 8.

The effect of Modification 3 is to increase the reliability from 0.843 to 0.946. Further, since the only likely use of the 10-flash limit in the optical beacon is to prevent continuous flashing by ground command, the value of this function should be estimated so that a decision, based on the reliability assessment of Reference 8, can be made as to whether this function should be retained.

REFERENCES

1. PRC TAM No. 106-1, GEOS Command Subsystem, PRC D-1022, 8 June 1965

2. PRC TAM No. 106-2, Contribution of Alternate Optical Logic to the Reliability of the GEOS Optical Beacon Electronics, PRC D-1023, 8 June 1965

3. PRC TAM No. 106-3, Analysis of and Observations Relating to Power Supply Subsystem, PRC D-1024, 8 June 1965

4. PRC TAM No. 106-4, Assessment of Thermal Design of the GEOS A Spacecraft, PRC D-1025, 8 June 1965

5. PRC TAM No. 106-5, Analysis of Gravity Gradient Stabilization System Performance of GEOS A, PRC D-1026, 8 June 1965

6. PRC TAM No. 106-6, Component Part Failure Rate Assignments for Reliability Assessment of the GEOS Satellite, PRC D-1027, 8 June 1965

7. PRC TAM No. 106-7, Reliability Analysis of De-Spinning Capability of GEOS A with Special Emphasis on the Yo-Yo De-Spin Device, 21 July 1965

8. PRC TAM No. 106-8, GEOS A Optical Beacon Reliability Assessment, PRC D-1049, 13 August 1965

9. PRC TAM No. 106-9, GEOS A Power Supply Reliability Assessment, PRC D-1110, 11 October 1965

10. PRC TAM No. 106-10, Operational Reliability Assessment of the GEOS A Spacecraft, PRC D-1056, 20 August 1965

11. PRC TAM No. 106-11, GEOS A Telemetry Subsystem Reliability Assessment, PRC D-1116, 8 October 1965

12. Applied Physics Laboratory, Johns Hopkins University, RLL-65-044, Evaluation of Aerovox Cerafil Capacitors Type MC80V 13 September 1965

13. Applied Physics Laboratory, Johns Hopkins University, SDO 1004.4, Minutes of the GEOS Briefing and Design Review, 22, 26, and 27 January 1965, pp. 77-97

14. Goddard Space Flight Center, NASA, PACER 151-005, Evaluation, Aerovox Cerafil Capacitors, Type MC80V, 4 March 1965

ERRATA SHEET

RELIABILITY ASSESSMENT OF THE GEOS A SPACECRAFT

PRC R-760

1. Page iii, line 7 - Change 0.63 to 0.59.
2. Page 9, line 4 - Change 0.47V to 0.49V.
3. Page 31, equation (4) - Change 0.265 to 0.222.
4. Page 31, sixth line from bottom - Change 0.63 to 0.59.
5. Page 31, last line - Change 0.33 to 0.31 and 0.63 to 0.59.
6. Page 32, fourth line from bottom - Change 0.081 + 0.838V to 0.84(0.081 + 0.838V).